Assessing the performance potential of climate adaptive greenhouse shells

Chul-sung Lee[1]*, P. Hoes[2], D. Cóstola[3], and J.L.M. Hensen[2]

[1] *Dep. of Architectural Engineering, Hanbat National University, Deajeon, South Korea*
[2] *Dep. of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands*
[3] *Dep. of Mechanical Aerospace Engineering, University of Strathclyde, Scotland, United Kingdom*

Abstract

Agriculture is responsible for 7.2% of the final energy consumption in the Netherlands; most energy is used for heating and lighting in the greenhouse sector. Currently, the greenhouse sector faces major challenges in reducing its energy demand while increasing crop quality and quantity. One route to improve the performance of industrial greenhouses could be based on using climate adaptive shells. These shells are capable of changing their thermal and optical properties on an hourly, daily, or seasonal basis to optimize performance. The climate adaptive shell concept shows considerable potential for performance improvement in the building sector. However, its potential for the greenhouse sector is yet unknown. This paper quantifies this potential by predicting the energy savings and the increase in net profit using a new framework based on numerical simulation and optimization techniques. The simulation results show that climate adaptive greenhouse shells increase net profit between 7% and 20 % for tomato producing Dutch greenhouses. Monthly and hourly adaptation resulted in considerable primary energy savings of 23% and 37%, respectively. It is expected that the predicted net profit increase and energy savings will drive the attention of the greenhouse industry towards the development of climate adaptive greenhouse shells.

Keywords: *climate adaptive greenhouse shells, multi-objective dynamic optimization, adaptation period, greenhouse performance simulation*

**Corresponding author:*

Chul-sung Lee (cslee.skor@gmail.com)

1. Introduction

The agricultural and horticultural sectors represent a large part of the industrial energy consumption in Northern European countries [1]. Due to the climate in Northern Europe, many agricultural and horticultural growers utilize greenhouses with heating systems in order to provide favorable conditions for crop production [2-3]. As a result, the Dutch agricultural sector was responsible for 7.2% of the final energy consumption of the Netherlands in 2014, and natural gas represented more than 60 % of the energy mix of the sector [4]. Most of this energy was used in greenhouses where it represented around 20% ~ 30% of total production costs of the crops [5]. In addition to cost of energy, this industry is facing increasingly stringent energy use targets to reduce CO2 emissions from national and European legislation [6]. This shows that the greenhouse sector faces major challenges to reduce its energy demand while increasing crop quality and quantity.

In the Netherlands, the vast majority of commercial greenhouses use glass as the major component of the greenhouse shell. Glass is used due to its stable optical properties and its durability. However, glass has a relatively low thermal performance (e.g. high U-value and high emissivity), which has a significant impact on the energy costs for operating the greenhouse and also has implications for crop yield. In order to improve the thermal performance and crop production of greenhouses, various studies attempted to optimize the use of existing materials for greenhouse shells and others have introduced new, innovative materials and designs. These studies can be grouped into four thematic areas: 1) increasing the solar transmittance of the shell, for example by using Fresnel lenses [7], laser-cut panel glazing [8], anti-drop (anti-condensation) films [9-10], or anti-reflective coatings [11]; 2) increasing the thermal performance of the shell, for example with a Zigzag sheet [12] or low emissivity coatings [13-14]; 3) controlling or filtering of solar radiation, for example with NIR reflecting films [15-19], Photo selective films [20-23], or UV blocking films [24-25]; and 4) studies aimed at improving the greenhouse performance by integrating renewable energy systems, for example by using Fluorescent solar concentrators [26-28], Fresnel lenses with T, PV and PVT [29-32], or semi-transparent photovoltaic modules [33-35].

Some new greenhouse concepts have been developed in recent times: for example, the solar greenhouse [36], the semi-closed greenhouse [37-41], the energy producing greenhouse [42], the Sunergy greenhouse [43], and the electricity generating greenhouse [44-45]. Most of the greenhouse concepts reduced energy use while maintaining or increasing the crop production. These previous greenhouse concepts are largely based on existing energy-saving technologies.

An alternative route to improve the performance of greenhouses could be based on the development of climate adaptive shells, which are capable of changing their thermal and optical properties on an hourly, daily, or seasonal basis to optimize performance in the face of changing boundary conditions [46]. The climate adaptive shell concept has shown considerable potential for performance improvement in the building sector [47-49], but the potential benefits in the greenhouse sector are unknown.

According to a model-based greenhouse design method [50-51], outdoor climate has the greatest impact on the greenhouse performance. This paper aims to identify the potential for energy saving and crop production increase in greenhouse shells capable of adapting to the weather conditions by changing several shell properties in various frequencies (monthly and hourly adaptation). At present, there are no cost-effective technologies capable of providing high levels of adaptation for greenhouse shells. By providing figures on potential savings, this paper aims to support building component developers and greenhouse contractors in making informed decisions to allocate research and development resources towards *climate adaptive greenhouse shells* (CAGS).

The CAGS performance assessment methodology introduced in this paper is based on dynamic simulation [52] and multi-objective optimization using genetic algorithms [53]. While both techniques are widely used in research, there are considerable challenges when optimizing shell properties during simulation runtime. For this purpose, a simulation-optimization framework was developed to assess the potential of CAGS. This framework is briefly presented in Section 2. Section 3 investigates the potential of CAGS through a case study with a tomato production greenhouse in the Netherlands. Section 4 shows the results of the case study and Section 5 discusses future developments and the control of the CAGS. Finally, Section 6 summarizes the main findings of this research.

2. Methodology

The main aim of this section is to arrive at a means to evaluate the potential of the proposed CAGS concept. Since there are currently no real-world applications to study in the field, the potential of the CAGS concept will have to be demonstrated by other means. In situations where new and innovative building designs need to be put to the test, computational assessment through the use of simulation tools has proved to be extremely useful. Therefore, in this study we also use a simulation approach to assess the performance of CAGS. This section first introduces a simulation tool for greenhouse performance simulation. Next, a simulation approach is described based on multi-objective optimization. Lastly, it is explained how the simulation approach is implemented in a simulation toolchain.

*2.1 **Greenhouse performance simulation tool***

A greenhouse performance simulation (GPS) tool needs to consider the combined effects of the many aspects that could influence the energy performance and productivity of a greenhouse [55], such as: all physical phenomena (conduction, convection, long and short-wave radiation, mass flow including air and moisture), heating and cooling systems, controls (shading devices, window opening/closure), and other operational issues (crop type, crop growth, CO_2 concentration). A literature review revealed the existence of several simulation tools that can address these aspects with various degrees of complexity and accuracy, such as KASPRO [54] and Greenhouse Environment Simulator [56]. In order to assess the performance of CAGS, it is necessary to vary the thermal and optical properties during simulation runtime [57]. However, this is not possible in the existing GPS tools. Moreover, the source-code of these tools is not open to third parties, which hinders their usage in the evaluation of CAGS. For this reason, this research adopted the widely validated open-source building energy simulation program, ESP-r [58-59], as the main simulation engine to assess the performance of the CAGS concept. ESP-r is a state-of-the-art BPS tool and it has significant power in modelling building physics. ESP-r has highly resolved and well validated methods for modelling the interactions between the indoor and outdoor environment and the building fabric [60]. ESP-r provides a small simulation time step for accurate calculations, and also offers flexibility and connectivity for both the control of shell properties and for coupling optimization algorithms from other tools.

In order to use ESP-r as a GPS tools, the authors had to extend and adapt a number of modelling aspects of ESP-r. The following key functions for greenhouse modelling were added/adapted (see also Figure 1): sky temperature, photosynthesis and respiration, transpiration and evaporation, humidification, condensation, ventilation control, artificial lighting control, screen control and transitivity of greenhouse roof. Furthermore, the authors would like to emphasize the integration of a crop model to calculate the crop production for given environmental conditions. This extended ESP-r version was validated with the state-of-the-art greenhouse performance simulation tool, KASPRO [61].

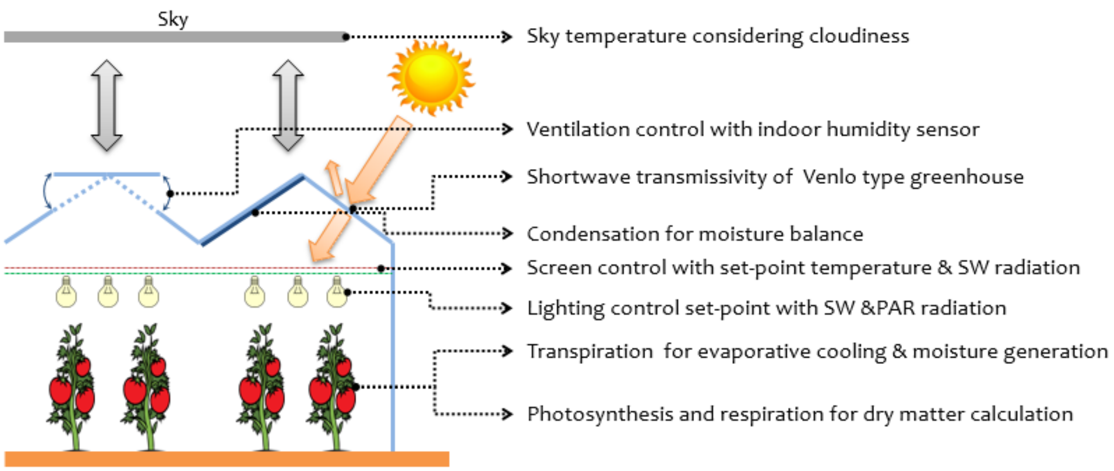


Figure1. Overview of features added to ESP-r for greenhouse performance simulation

2.2 Multi-objective optimization of shell properties per adaptation period

The CAGS concept changes or 'adapts' its shell properties (e.g. transmittance or emissivity) in reaction to changes in climate conditions to meet predefined objectives. In order to assess the potential of CAGS, the simulation tool should find the optimal values of the shell properties for each 'adaptation period' during the required assessment period. Note that in this work we define the 'adaptation period' as the period between changes of the shell properties; the length of this adaptation period can be hours, days or months (later in this article we will discuss the optimal length of this adaptation period). There are various methods that can be used to search for the optimal values of the shell properties, ranging from brute force search methods to gradient-based methods and genetic algorithms [62]. Genetic algorithms (GA) have been successfully used in a variety of applications in the building domain [63], therefore a GA was also chosen to optimize the shell properties in this study. The overall simulation approach including the GA is illustrated in Figure 2 and described in detail below.

As mentioned above, the proposed simulation approach needs to find the optimal values for the shell properties during the whole assessment period (T0 ~ Tn). Each adaptation period (Ap) will have one set of optimal values for the shell properties. For each assessment period, the number of sets with optimal values is dependent on the length of the adaptation period (A_{px} ~ Ap_{x+1}). In this example, at time Ap_x, the master simulation pauses and sends its state values (air temperatures, surface temperatures, etc.) to the shell optimizer. The optimizer evaluates various sets of shell property values (S1 ~ S6), defined by the GA algorithm, for the duration of the adaptation period by using the extended ESP-r tool. The calculated results (R1 ~ R6, corresponding to S1 ~ S6) are compared. The optimal set of shell properties (S6) that shows the desired performance (R6) is selected and returned to the master simulation. Finally, the master simulation continues with the current adaptation period (Ap_x ~ Ap_{x+1}) and implements the optimal set of shell properties (S6). Next, the optimization moves to the next adaptation period (Ap_{x+1} ~ Ap_{x+2}). Using this simulation approach, the CAGS concept can be evaluated without losing any historical thermal effects in the growing medium (in our case, soil) during the assessment period.

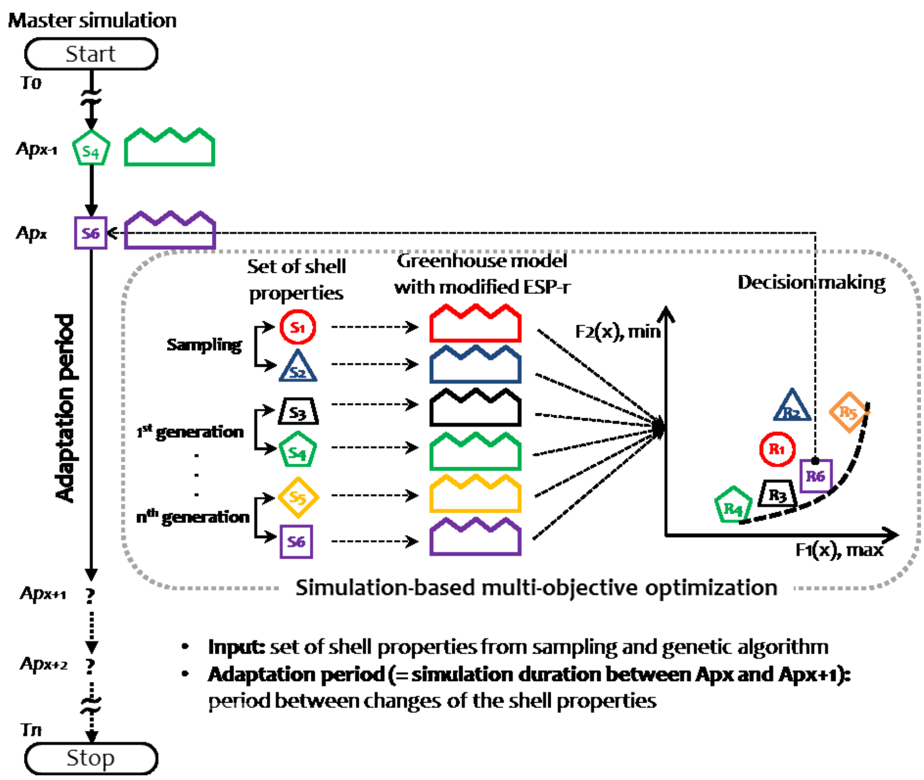


Figure2. Schematic description of multi-objective dynamic optimization for the CAGS concept

2.3 *Virtual test environment for CAGS concept*

This section describes the implementation of the simulation approach in a simulation toolchain. The simulation toolchain in this study is based on previous research [65] and uses co-simulation. Co-simulation means that two or more separate programs are coupled and exchange data at run-time. Co-simulation makes it possible to extend the capabilities of a single tool and to manage complicated and innovative systems [64], such as the CAGS concept. As shown in Figure 2 the simulation approach in this study consists of a master simulation (running for the whole assessment period) and an optimizer (running multiple times for each adaptation period). Co-simulation is used to couple the master simulation with the optimizer at simulation run-time.

In this study the toolchain consists of ESP-r, Matlab and the BCVTB. ESP-r represents the model of the CAGS greenhouse, Matlab acts as the greenhouse shell optimizer/controller, and the BCVTB operates as middleware. The BCVTB (Buildings Control Virtual Testbed) [66] is a software environment that allows different simulation programs to be connected and to exchange data during runtime, and it allows for conducting hardware in the loop simulations. The software can be used for co-simulation and for real-time simulations.

In the proposed simulation approach the GA uses many iterations (hundreds) in each adaptation period to find the optimal shell property values. Per adaptation period, each iteration should use the same initial boundary conditions. In order to use the same initial boundary condition and decrease state initialization time, Hoes [67] proposed overwriting the state values of the conservation equations at the start of each simulation. This method is also applied in this study. The various steps in the simulation toolchain are described in more detail below and are presented in Figure 3.

The simulation starts with ESP-r. ESP-r simulates the CAGS concept and pauses just before the start of the next adaptation period. Then, ESP-r sends its state variables (as sensor values) to the controller via BCVTB and waits for an optimal set of shell properties from the greenhouse shell optimizer/controller. Matlab, which uses the same greenhouse model as the master simulation, uses the received state variables to initialize the model and starts the optimization using the GA to search for optimal shell properties for the adaptation period. In the optimization process, this research uses the Non-Sorting Genetic Algorithm-II (NSGA-II) as the GA and the Latin Hypercube Sampling (LHS) method to create the initial population. The optimization stops when the stopping criteria are met. When the optimization is finished, an optimal set of shell properties is automatically selected by means of predefined decision-making rules. These rules are based on an economic approach that calculates the 'net profit'; this approach is described in more detail in Section 3.1.1. Then, Matlab sends the optimal shell property values to the master simulation. Next, the master simulation continues with the received optimal values for the next adaptation period. This process continues until the end of the assessment period.

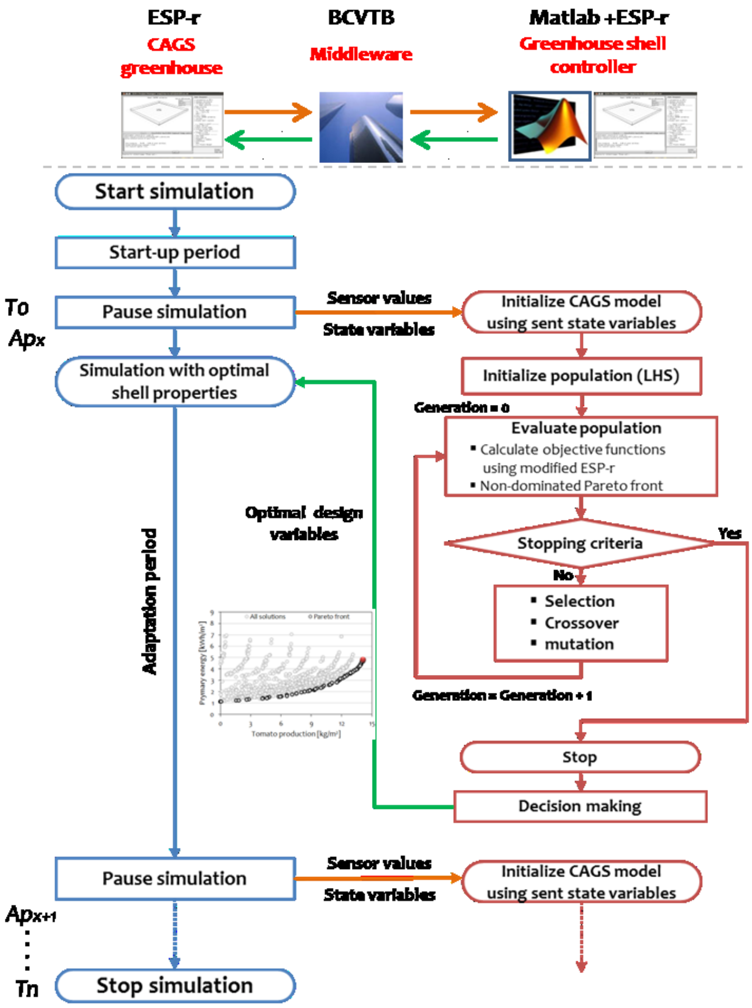


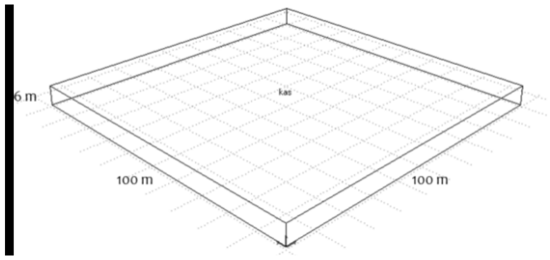
Figure3. Toolchain for implementation of dynamic optimization for CAGS concept

3. Case study description

The potential of the CAGS concept is demonstrated in a case study. This section first introduces the greenhouse case study model and then describes the two key performance indicators that are used to assess the performance of the greenhouse design. Furthermore, the rules for decision making in order to choose between the various shell sets is discussed.

3.1 Greenhouse case study model

The case study greenhouse is based on the widely used Venlo-type greenhouse in the Netherlands. In this case study the greenhouse grows tomato crops. The case study greenhouse was modelled in ESP-r, as shown in Figure 6, based on properties available in the literature [54]. The boundary conditions of the four walls are set as adiabatic, since it is assumed that the optical and thermal effects from the walls are small and can be neglected for this large low-rise greenhouse [54]. Openings on the roof are available for ventilative cooling and dehumidification, and are modelled using an airflow network [70]. It is assumed that half of the openings face the south and the other half face the north. The roof appears flat in the schematic of the simulation model, but the simulation takes into account the angular dependence of a saw tooth roof for incident solar radiation.



Location: De Bilt, The Netherlands
Opening size[m^2]: 3.25
Opening fraction [m^2/m^2]: 0.0417
U shell - value [$W/m^2 \cdot K$]: 5.75
ε shell inside: 0.84
ε shell outside: 0.84
τ shell SW radiation: 0.85
α shell SW radiation: 0.04
ρ shell SW radiation: 0.11

Figure 6. Simulation model of reference greenhouse for tomato growing.

Figure 7, below, provides a brief overview of the assumptions of the system and controls of the greenhouse. The greenhouse is heated with a boiler with $\eta_{overall\_boiler} = 0.9$ and is cooled by natural ventilation. Indoor relative humidity is controlled by natural ventilation with $\eta_{ventilation} = 0.5$ and mechanical ventilation by fan with $\eta_{ventilation} = 1.0$. A ventilation efficiency of 0.5 means that ventilation transfers only 50% of moisture to the air exchange and this is only applicable for the dehumidification. CO_2 is supplied during day time to meet a concentration of 800ppm at each time step, but the concentration changes depending on the ventilation. Indoor air temperature is controlled with hourly set-points commonly used by Dutch tomato growers. Two screens, one aluminized and one transparent, are used to reduce energy losses in times with low solar radiation and cold weather. All detailed control and set point of the screens and fan ventilations are described in [54].

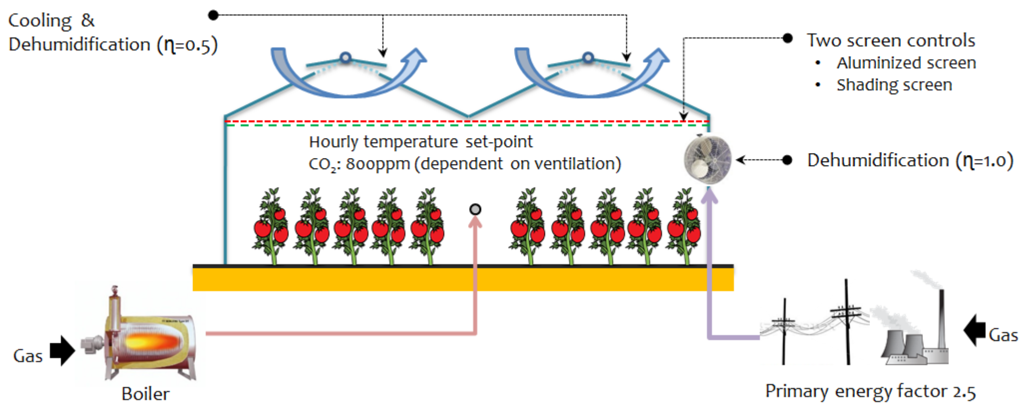


Figure 7. Overview of control and operation of the case study greenhouse.

This study used a Dutch weather file of the typical reference year of 2009 from KNMI [71]. Figure 8 shows the hourly weather conditions regarding air temperature, global horizontal irradiance (GHI), wind speed and relative humidity.

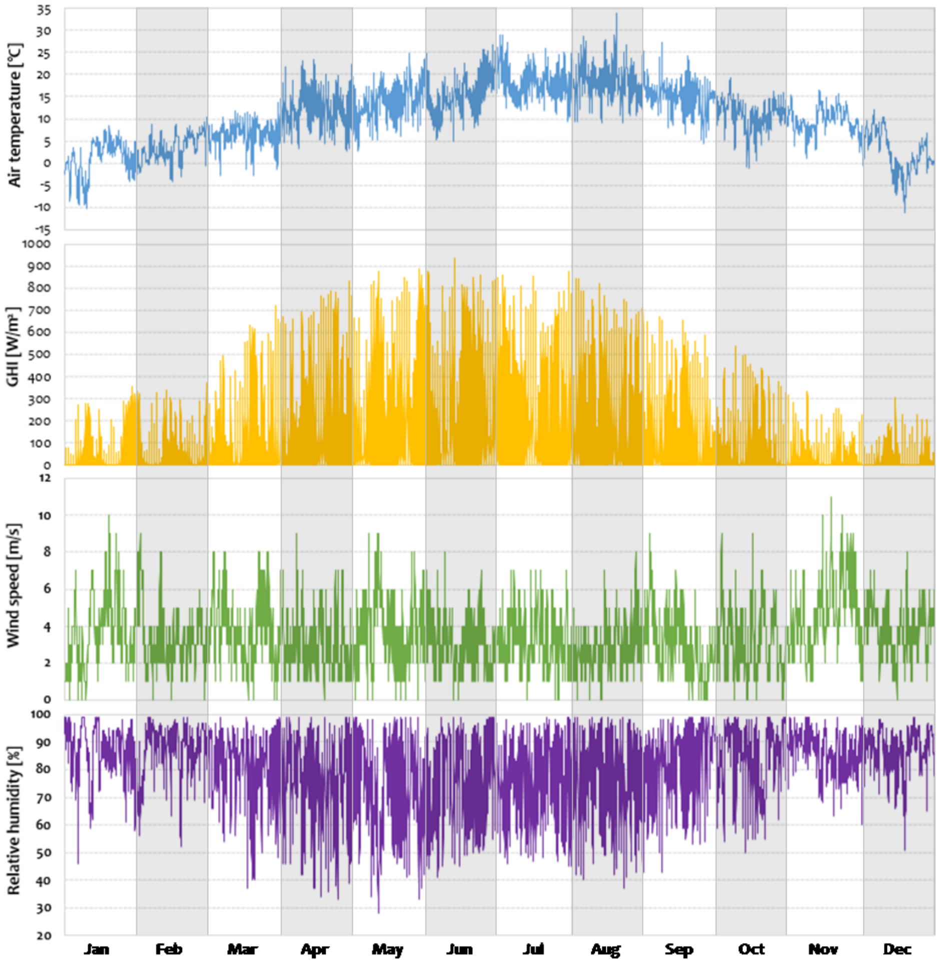


Figure 8. Hourly weather condition of air temperature, global horizontal irradiance (GHI), wind speed, and relative humidity

3.2 Performance indicators and objective function

The potential of the CAGS concept is evaluated using the following two performance indicators (PI): primary energy consumption and crop production. The optimal greenhouse is determined by using these performance indicators and a decision-making strategy.

The case study uses a gas boiler for heating and fans for cooling and dehumidification. Both the gas consumption and the fan's electricity consumption are calculated in the simulation. These two energy consumptions are converted into primary energy (gas) with a primary energy conversion factor of 1.1 (1/0.9) for heating (which is derived from $\eta_{overall\_boiler}$=0.9) and 2.5 for electricity.

The simulation tool calculates the amount of fresh matter (FM) production in kilograms from dry matter (DM) production calculated using the tomato crop model implemented in ESP-r. A fresh matter conversion factor of 10 was adopted. In order to facilitate decision making with the two conflicting PIs, this case study used Pareto optimization with a 'posteriori' approach. This means that the optimal solutions (in this case, an optimal solution is a set of optimal shell properties) have to be found before the decision is made. As shown in Figure 4, the optimal solutions from Pareto optimization are a set of non-dominated solutions.

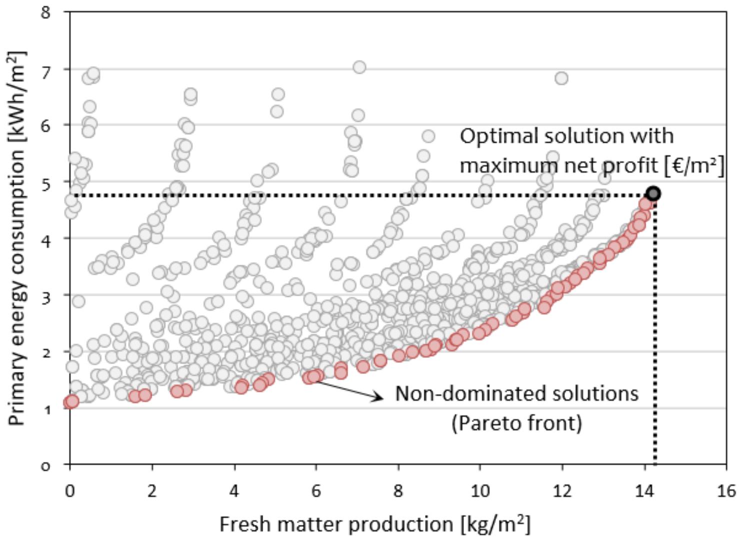


Figure 4. An example of selection of the optimum solution with maximum net profit in August.

A practical approach to decision making to select an optimal solution for greenhouse design in this context can be found in [68]. The study evaluated the results of different solutions by investigating the resulting annual net financial results (NFR) of each option, which was complicated. However, this case study adopts a simple approach to calculates the 'net profit' and determine an optimal solution for this multi-objective optimization problem. To do this, both tomato production and primary energy consumption are converted into Euros per square meter. This conversion then allows the calculation of the net profit (Q_{net_profit}), which is used for decision making:

$$Q_{net\_profit}(t_f) = \int_{t_0}^{t_f} Q_{tomato\_yield} - Q_{p\_energy}\, dt \qquad [€/m^2]$$

Where t_0 and t_f are the beginning and the end of the adaptation period respectively, Q_{tomato_yield} (€/m^2) is tomato production, and Q_{p_energy} (€/m^2) is the primary energy consumption. The primary energy consumption (Q_{p_energy}) is calculated by:

$$Q_{P\_energy} = \{(E_{gas} * 1.1) + (E_{eletricity} * 2.5)\} * q_{gas} \qquad [€/m^2]$$

Where E_{gas} (kWh/m^2) is gas consumption, $E_{eletricity}$ (kWh/m^2) is electricity energy consumption, and q_{gas} (€/kWh) is gas price. The tomato production (Q_{tomato_yield}) is calculated by:

$$Q_{tomato\_yield} = FM_{har} * q_{tomato} \qquad [€/m^2]$$

Where, FM_{har} (kg/m^2) is harvested tomato production and q_{tomato} (€/kg) is tomato price. Since the tomato price varies over the year, this study took monthly averages from [69], which is illustrated in Figure 5.

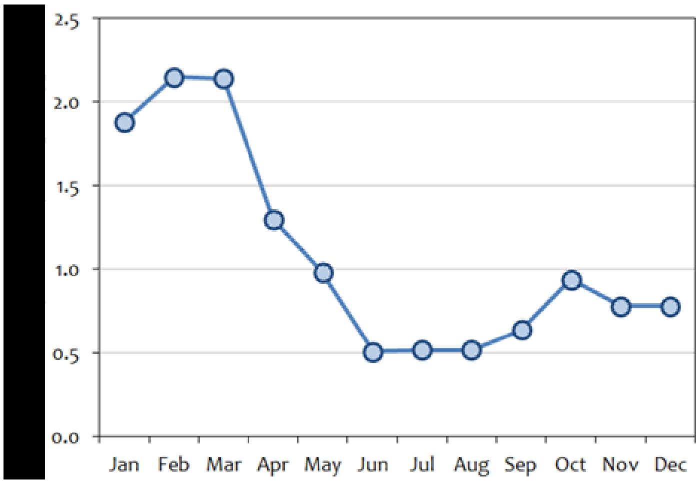


Figure 5. Average monthly tomato price in The Netherlands [69]

When the adaptation frequency is high, adaptation periods may occur in which no PI is considered (e.g. a CAGS concept greenhouse with passive cooling in summer). However, at least one PI, which becomes the objective function in an optimization problem, is necessary for the decision making. This study employs 'average setting temperature' to select the optimum solution. The average setting temperature is the average of the heating and cooling set points, and the optimum solution will be the set of properties that has the closest air temperature to the average setting temperature.

3.3 Design parameters for optimization

Table 1 presents the thermal and optical greenhouse parameters to be optimized with ranges also described in this table. The parameters were selected for the CAGS by sensitivity analysis [54] and ranges were set to cover the main factors affecting the primary energy consumption of the greenhouse. Note that the U-value and emissivity of the greenhouse shell are considered as two separate parameters, although the U-value varies depending on the inside and outside emissivity. The U-value and emissivity are presented in this manner since the U-value is used extensively as an indicator of thermal performance. However, calculations in ESP-r uses the thermal conductivity of the glazing rather than the U-value itself.

Table 1 Selected greenhouse design parameters of greenhouse shell and considered ranges

Parameters	**Range**	**Description**
τ-PAR [-]	0.05 ~ 0.95	Transmittance of photosynthetically active radiation
τ-NIR [-]	0.05 ~ 0.95	Transmittance of near-infrared radiation
U(s)-value [W/m^2·K]	0.8~5.8	U-value of shell calculated by ISO 6946
ε-inside [-]	0.05 ~ 0.95	Inside emissivity
ε-outside [-]	0.05 ~ 0.95	Outside emissivity

4. Case study results

In this section the potential of the CAGS concept was demonstrated by simulating a greenhouse shell with adaptive shell properties and comparing its performance to a reference greenhouse with fixed shell properties. The Venlo-type greenhouse was used as this reference greenhouse. Furthermore, the optimal shell property values and the sensitivity of the design parameters over the year are investigated.

4.1 Performance improvement compared to static shells

In this section the reference greenhouse was compared to an optimized static greenhouse and a greenhouse with CAGS considering two adaptation frequencies (monthly and hourly adaptation). The optimized static greenhouse represents a greenhouse with optimal shell property values for the year, i.e., no adaptation during the year. Figure 9 shows the predicted performance of all the greenhouses. The graphs show the tomato production, the energy consumption and the net profit. The optimized design and the CAGS concept showed a higher net profit compared to the reference greenhouse. The difference in net profit between the optimized static greenhouse (7% compared to the reference greenhouse) and the monthly adaptive greenhouse (9% compared to the reference greenhouse) was small. Note that the highest profit is not necessarily associated with the maximum production nor with the minimum energy consumption. This is a result of the trade-off between the two objectives during the decision making to maximize the net profit. The hourly adaptive greenhouse showed the highest potential in terms of tomato production increase, primary energy saving and finally net profit increase (20% compared to the reference greenhouse). It can be concluded that once the greenhouse design is optimized for this tomato crop, monthly adaptation does not lead to many advantages in financial terms, but hourly adaptation demonstrates great potential to provide significant performance improvement.

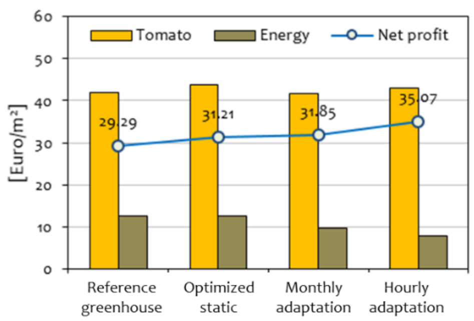


Figure 9 Simulated results of tomato production, energy consumption and net profit

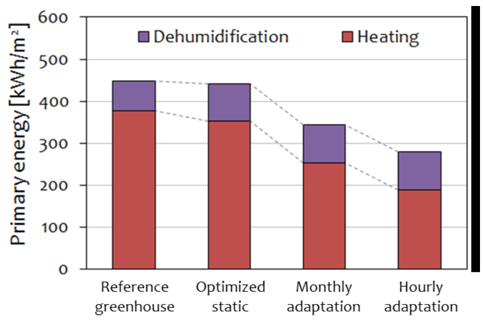


Figure 10 Distribution of primary energy consumption.

Figure 10 shows the energy consumption over the year for dehumidification and heating. The optimized greenhouses used more energy for dehumidification compared to the reference greenhouse. This was caused by the used ventilation strategy, which aims to increase the tomato production by maintaining a high CO_2 concentration. This case study used two ventilation systems for dehumidification: mechanical ventilation with a ventilation efficiency of 1, and natural ventilation with a ventilation efficiency of 0.5. Therefore, in order to minimize air change, which leads to CO_2 decrease, the optimization algorithm forces the use of mechanical ventilation with high ventilation efficiency rather than natural ventilation. The difference in heating energy consumption between the reference greenhouse and the optimized static design was small; however, the adaptive greenhouses showed 23% ~ 37% of heating energy saving compared to the reference greenhouse.

These results showed that the climate adaptive concept provides many opportunities to reduce the use of heating energy. Although little financial return was visible when comparing the optimized static design to the monthly adaptive CAGS, the monthly adaptive concept was still promising in terms of CO2 reduction. In order words, the CAGS concept showed a clear advantage over the conventional static greenhouse designs.

*4.2 **Optimum properties and their sensitivity***

This section provides an in-depth analysis of the CAGS simulation results. This analysis presented the optimal values of the shell properties over the year together with the sensitivity of each property. The sensitivity index was calculated during the optimization process. It is important to consider the optimal value and the sensitivity at the same time in order to determine which optimal property is important for the greenhouse performance. These results could inspire the designs of future greenhouse shells; what properties should be made adaptive and what values (ranges) should these properties have?

4.2.1 Optimized static and monthly adaptive shell

The two graphs in Figure 11 provide optimal static and monthly property values and sensitivities. For most parameters, there was a clear transition from winter to summer. In the winter, low U-values and emissivity of the inside face of the shell worked to reduce energy losses and therefore to reduce heating energy consumption. This was combined with high NIR transmittance to increase solar gains and reduce energy needed for heating. In the summer, high U-values and emissivity of the inside face of the shell worked to facilitate heat losses, reducing the need for ventilative cooling and therefore maintaining high CO_2 levels inside the greenhouse. Optimal behavior of CAGS in mid-season were in between winter and summer. Sensitivities in Figure 11 support this analysis, as there is a clear shift from positive to negative sensitivities as seasons change. PAR transmittance was always high, as expected, due to its beneficial effect on photosynthesis (or tomato production). Outside surface emissivity was the least sensitive parameter and shows erratic behavior over the year as it was not a dominating factor in the overall performance. When comparing the optimized static shell with the monthly adaptive shell, the optimized static shell showed to be a compromise of the optimal monthly adaptive shell values.

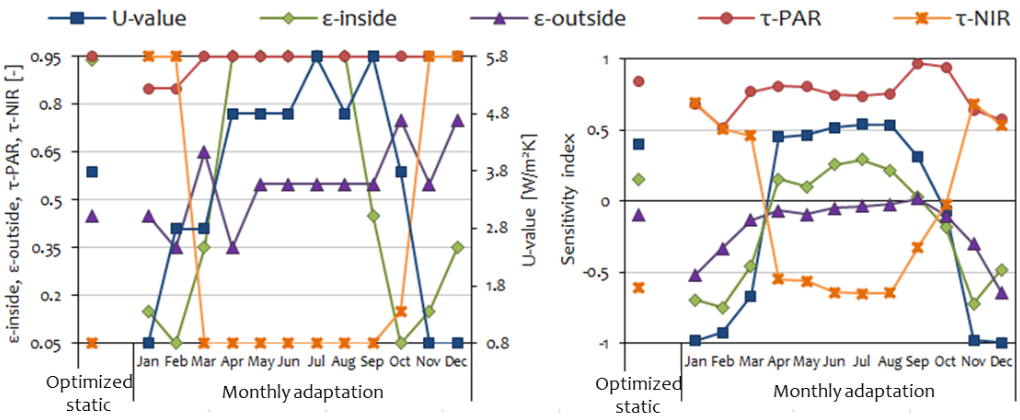


Figure 11 Optimum properties (left) and their sensitivity (right) of the optimized static shell and the monthly adaptive shell

4.2.2 Hourly adaptive shell

Hourly optimal property values were not constant but varied over the day (due to the continuously changing performance requirements and weather conditions). Although the hourly variations of the optimal properties are useful to see, the fluctuations make it difficult to interpret the result visually. In order to focus on long term variations, this study showed the hourly optimal properties and sensitivity index using a 'moving average' [72]. The moving average method avoids short-term variations and highlights long-term trends in data. In addition, the analysis was divided into day and night to avoid combining the influence of the sun.

Figure 12 showed the optimum properties and sensitivity of the hourly optimized shell during day time with a moving average of five days. The variation of U-values showed similar behavior to the monthly adaptive shell over the year: low in winter to minimize heat loss and high in summer to maximize heat elimination. The variation of U-value showed more influence in winter on net profit increase resulting from energy saving than in summer. PAR transmission was always high and was the most influential property in mid-season and in summer when tomato production begins. The trade-off between energy saving and production increase resulted in fluctuation and low sensitivity of PAR transmission in winter. This was because increases in PAR led to increases in relative humidity that must be removed, which leads to an increase in energy demand for ventilative cooling. Optimal inside and outside emissivity showed no clear change over the year since variations of these properties were not significant in the net profit increase. This low sensitivity was likely related to the changes of shell properties every hour, which was to focus on the identification of dominating shell properties (PAR transmittance and U-values).

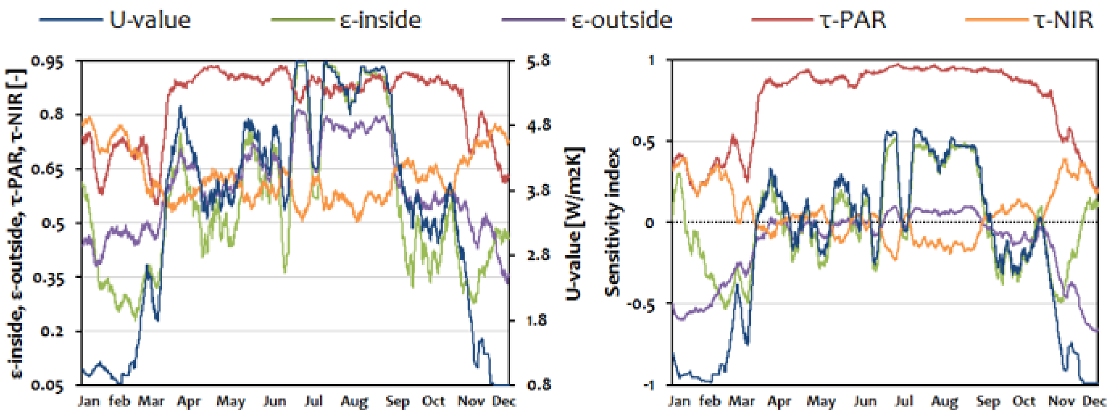


Figure 12 Optimum properties (left) and their sensitivities (right) of the hourly adaptive greenhouse shell during day-time with five days of moving average

Figure 13 shows optimum properties and sensitivities of the hourly optimized greenhouse shell during night time. Since the tomato crop is not engaged in photosynthesis at night, the optimization turns into a single-objective problem that only needs to minimize primary energy consumption. During night time, the optical properties are not relevant, and therefore only the three thermal properties were discussed below. All three properties showed a high influence during the winter. The optimal U-value and outside emissivity value were low to prevent heat losses to the outside. The crop also emits moisture at night time leading to an increase in humidity. For humidity control, this greenhouse used condensation or ventilation. Considering crop growth and heat preservation in winter, using condensation is a more efficient method than using ventilation since there is no air exchange required. In order to increase condensation, the greenhouse shell temperature should be low enough to result in a positive sensitivity index and a high optimal value of inside emissivity. During summer, the sensitivity index and the optimal property did not show any relation each other. This lack of connection is caused by the decision-making criteria of the average setting temperature. As defined in Section 3.1.1, there were some periods without any heating, cooling or dehumidification demand when the CAGS concept greenhouses had a high adaptive frequency. Since some values should be selected to find an optimal solution, the average setting temperature was employed to substitute primary energy consumption.

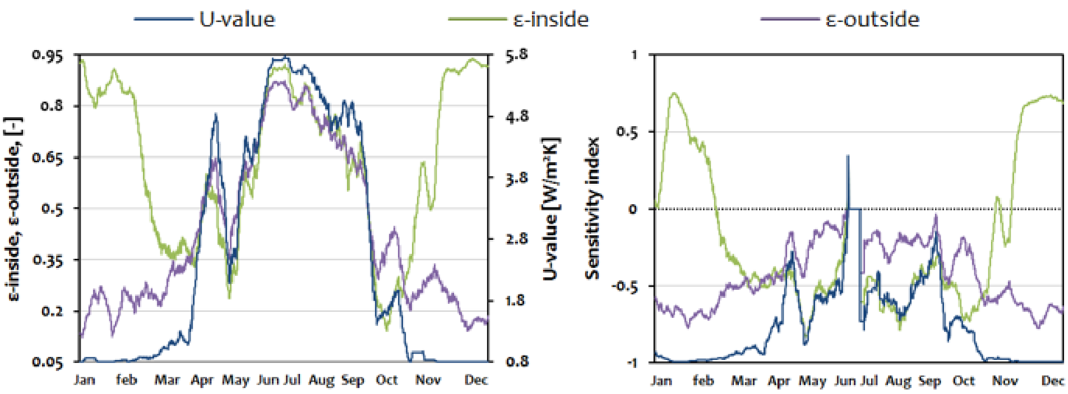


Figure 13 Optimum properties (left) and sensitivity (right) during night-time with five days of moving average.

5. Discussion towards the development of CAGS

The results in Section 4.2 showed the optimal variation of the shell properties depending on the length of the adaptation period and showed the sensitivity of each shell property with respect to the performance indicators. This information can help developers to identify which shell properties they should focus on for future development of CAGS. The future developments depending on the adaptation period are discussed in this section.

Static optimal greenhouse shell: In order to maximize net profit with a static greenhouse shell, the optical properties of the shell should maximize PAR transmission to achieve maximum photosynthesis, and should minimize NIR transmission to achieve minimum evaporative cooling, high CO2 concentration and reduced ventilation. The heat insulating performance should not be excellent (around 3.8 W/m^2K) when applying both ventilative cooling and CO2 supply in summer, since maintaining high CO2 concentration returns in high net profits.

Monthly adaptive greenhouse shell: The shell should be developed so that U-value, internal emissivity and NIR transmission can be controlled per season. Control of PAR transmission is not necessary to maximize net profit over the year. The control strategies are: the shell should have low U-value and internal emissivity and high NIR transmittance in winter; in contrast, the shell should have high U-value and internal emissivity and low NIR transmittance in summer and mid-season.

Hourly adaptive greenhouse shell: The hourly optimal shell characteristics and sensitivity were shown by the moving average technique in Section 4.2.2, so that only long-term shell characteristics and sensitivity can be confirmed. From the sensitivity analysis, this study found that the greenhouse shell should be developed so as to control the U-value, the inside and outside emissivity, and the PAR transmittance. The long-term control method was shown in Figure 12 and Figure 13, but the hourly operating method is not determinable. Figure 14 showed the hourly optimum shell properties during the summer, mid-season and winter. Some optimal shell properties, such as U-value in winter and PAR transmittance in summer, do not change significantly even between day and night. However, most optimal shell properties varied greatly over time depending on continuously changing external environment conditions and internal requirements.

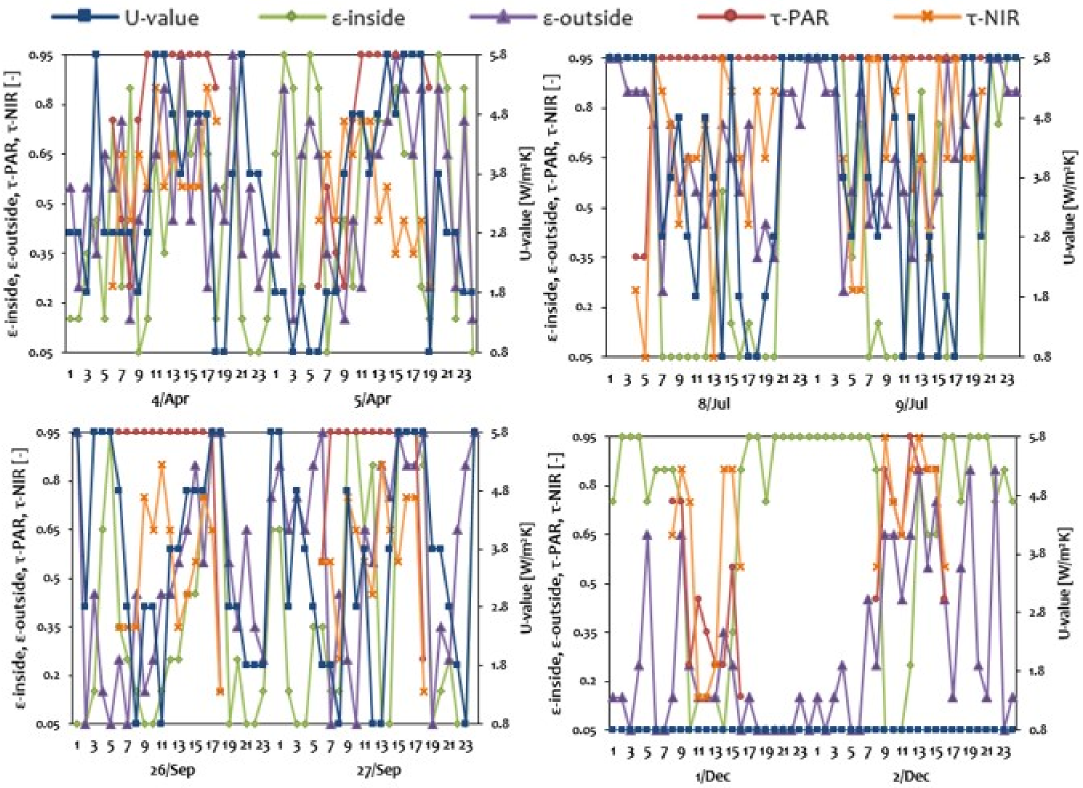


Figure 14 Hourly optimal properties in summer (8/Jul ~ 9/Jul), mid-season (4/Apr ~ 5/Apr and 26/Sep ~ 27/Sep) and winter (1/Dec ~ 2/Dec)

6. Conclusion

This study proposes Climate Adaptive Greenhouse Shells (CAGS) as a new, future greenhouse concept. The performance of the CAGS concept was computationally investigated in a case study. It is important to note here that the CAGS concept greenhouse differs from the typical Dutch greenhouse in the following key aspects: the CAGS greenhouse concept varies in regard to five thermal and optical properties, which were selected for the CAGS concept by sensitivity analysis. The performance of the different greenhouse concepts is compared via a calculation of the generated net profit. The net profit of an optimized static greenhouse and the CAGS concept with two adaptation periods (monthly and hourly adaptation) are compared to a reference greenhouse (a Venlo-type Dutch greenhouse) growing tomatoes. The results of the case study are described below.

- Climate adaptive greenhouse shells increase the net profit between 7% and 20% compared to the reference greenhouse.
- Monthly and hourly adaptation showed little tomato production increase, but did demonstrate considerable primary energy savings of 23% and 37%, respectively.

- The CAGS concept with the higher adaptation frequency demonstrated greater potential in terms of primary energy saving and thus net profit increase.

Next, an in-depth analysis was performed of the CAGS simulation results. This analysis presents the optimal values of the shell properties over the year together with the sensitivity of each property. The results show that optical properties (PAR and NIR transmittance) are the most influential variables in the optimized static greenhouse and the CAGS concept greenhouse with monthly adaptation. U-value and PAR transmittance at day time and U-value and inside sensitivity at night time are the most influential variables in the CAGS concept greenhouse with hourly adaptation.

The climate adaptive greenhouse concept shows a great potential for the Dutch tomato greenhouses to reduce energy use (as well as CO_2 emissions) and increase net profit. This study only focused on tomato greenhouses with a specific heating and ventilation system and the specified performance requirements for the tomato crop. The potential of the CAGS was investigated further by testing five system concepts for three crops: tomato, phalaenopsis and chrysanthemum in [54]. The study demonstrated that the potential of the CAGS concept varies depending on the greenhouse systems and crop type.

Finally, note that this study did not consider additional increases in expenses, such as investment costs and maintenance costs, etc. Therefore, the technical and financial implications and viability should be addressed by future studies, and replication studies of the CAGS concept should be performed in the real world.

Acknowledgement

This research was funded by Ministry of Economic Affairs, Agriculture and Innovation, The Netherlands, as part of the project EOS-LT project – Climate Adaptive Glastuinbouw: Inverse Modelling (CAGIM). This financial contribution is gratefully acknowledged.

Reference

[1] Dehnen-Schmutz, K., Holdenrieder, O., Jeger, M., Pautasso, M., 2010. Structural change in the international horticultural industry: Some implications for plant health, In Scientia Horticulturae, Volume 125, Issue 1, Pages 1-15, ISSN 0304-4238

[2] Torrellas, M., Antón, A., Ruijs, M., Victoria, N., Stanghellini, C., Montero, J., 2012. Environmental and economic assessment of protected crops in four European scenarios, In Journal of Cleaner Production, Volume 28, Pages 45-55, ISSN 0959-6526

[3] Bayer, P., Saner, D., Bolay, S., Rybach, L., Blum, P., 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review, In Renewable and Sustainable Energy Reviews, Volume 16, Issue 2, Pages 1256-1267, ISSN 1364-0321

[4] Eurostat (2016), Retrieved August 29, 2018, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_energy_use

[5] Peet, M., Welles, G., "Greenhouse tomato production", Crop production science in horticulture series: Tomatoes, Ed. Heuvelink E., CABI Publishing, 2005, 257-304. Print

[6] Delbeke, J., Vis, P., 2016. EU Climate Policy Explained — European Union, Routledge, Retrieved August 29, 2018, from https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_en.pdf

[7] Kurata, K., 1991. Scale-model experiments of applying a Fresnel prism to greenhouse covering. Solar Energy, 46(1), pp.53–57

[8] Edmonds, I.R., Pearce, D.J., 1999. Enhancement of crop illuminance in high latitude greenhouses with laser-cut panel glazing. Solar Energy, 66(4), pp.255–265.

[9] Cemek, B., Demir, Y., 2005. Testing of the condensation characteristics and light transmissions of different plastic film covering materials. Polymer Testing, 24(3), pp.284–289.

[10] Pollet, I.V, Pieters, J.G., 2000. Condensation and Radiation Transmittance of Greenhouse Cladding Materials, Part 2: Results for a Complete Condensation Cycle. Journal of Agricultural Engineering Research, 75(1), pp.65–72.

[11] Rosencrantz, T., Bülow-Hübe, H., Karlsson, B., Roos, A., 2005. Increased solar energy and daylight utilisation using anti-reflective coatings in energy-efficient windows. Solar Energy Materials and Solar Cells, 89(2-3), pp.249–260.

[12] Sonneveld, P.J., Swinkels, G.L.A.M., 2005. New developments of energy-saving greenhouses with a high light transmittance. Acta Horticulturae, 691(1), pp.589–596.

[13] Dachselt, W.D., Münz, W.D., Scherer, M., 1982. Low emissivity and solar control coatings on architectural glass. Optical Coatins for Energy Efficiency and Solar Applications, 37, pp.37–43.

[14] Halleux, D., Deltour, J., Nijskens, J., Nisen, A., Coutisse, S., 1985. Dynamic simulation of heat fluxes and temperature in horticultural and low emissivity glass-covered greenhouse. Acta Hortic. (ISHS), 170, pp.91–96.

[15] Kempkes, F., Stanghellini, C., Hemming, S., Dai, J., 2008. Cover materials excluding near infrared radiation: Effect on greenhouse climate and plant processes. Acta Horticulturae, 797, pp.477–482.

[16] Kempkes, F.L.K., Stanghellini, C., Hemming, S., 2009. Cover materials excluding near infrared radiation: What is the best strategy in mild climates? Acta Horticulturae, 807, pp.67–72.

[17] Hemming, S., Kempkes, F., Van Der Braak, N., Dueck, T., Marissen, N., 2006. Filtering natural light at the greenhouse covering - Better greenhouse climate and higher production by filtering out NIR? Acta Horticulturae, 711, pp.411–416.

[18] Hemming, S., Kempkes, F., Van Der Braak, N., Dueck, T., Marissen, N., 2006. Greenhouse cooling by NIR-reflection. Acta Horticulturae, 719, pp.97–105.

[19] Kempkes, F.L.K., Hemming, S., 2012. Calculation of NIR effect on greenhouse climate in various conditions. Acta Horticulturae, 927, pp.543–550.

[20] Kittas, C., Baille, A., Giaglaras, P., 1999. Influence of Covering Material and Shading on the Spectral Distribution of Light in Greenhouses. J. Agric. Engng Res, 73, pp.341–351.

[21] Li, S., Rajapakse, N.C., Young, R.E., Oi, R., 2000. Growth responses of chrysanthemum and bell pepper transplants to photoselective plastic films. Scientia Horticulturae, 84(3-4), pp.215–225.

[22] Oyaert, E., Volckaert, E., Debergh, P.C., 1999. Growth of chrysanthemum under coloured plastic films with different light qualities and quantities. Scientia Horticulturae, 79(3-4), pp.195–205.

[23] Cerny, T., Faust, J., 2003. Influence of photoselective films and growing season on stem growth and flowering of six plant species. The American Society for Horticultural Science, 128(4), pp.486–491.

[24] Kittas, C., Tchamitchian, M., Katsoulas, N., Karaiskou, P., Papaioannou, Ch., 2006. Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. Scientia Horticulturae, 110(1), pp.30–37.

[25] Tsormpatsidis, E., Henbest, R.G.C., Davis, F.J., Battey, N.H., Hadley, P., Wagstaffe, A., 2008. UV irradiance as a major influence on growth, development and secondary products of commercial importance in Lollo Rosso lettuce "Revolution" grown under polyethylene films. Environmental and Experimental Botany, 63(1-3), pp.232–239.

[26] Novoplansky, a., Sachs, T., Cohen, D., Bar, R., Bodenheimer, J., Reisfeld, R., 1990. Increasing plant productivity by changing the solar spectrum. Solar Energy Materials, 21(1), pp.17–23.

[27] Hammam, M., El-Mansy, M. K., El-Bashir, S. M., El-Shaarawy, M. G., 2007. Performance evaluation of thin-film solar concentrators for greenhouse applications. Desalination, 209(1-3 SPEC. ISS.), pp.244–250.

[28] Lamnatou, C., Chemisana, D., 2013a. Solar radiation manipulations and their role in greenhouse claddings: Fluorescent solar concentrators, photoselective and other materials. Renewable and Sustainable Energy Reviews, 27, pp.175–190.

[29] Jirka, V. et al., 1999. Energy flow in a greenhouse equipped with glass raster lenses. Renewable Energy, 16(1-4), pp.660–664.

[30] Tripanagnostopoulos, Y., Souliotis, M., Tonui, J.K., Kavga, A., 2005. Irradiation aspects for energy balance in greenhouses. Acta Horticulturae, 691, pp.733–740.

[31] Tsormpatsidis, E., Henbest, R.G.C., Davis, F.J., Battey, N.H., Hadley, P., Wagstaffe, A., 2008. UV irradiance as a major influence on growth, development and secondary products of commercial importance in Lollo Rosso lettuce "Revolution" grown under polyethylene films. Environmental and Experimental Botany, 63(1-3), pp.232–239.

[32] Sonneveld, P.J., Swinkels, G.L.A.M., Van Tuijl, B.A.J., Janssen, H.J.J., Campen, J., Bot, G.P.A., 2011. Performance of a concentrated photovoltaic energy system with static linear Fresnel lenses. Solar Energy, 85(3), pp.432–442.

[33] Yano, A., Onoe, M., Nakata, J., 2014. Prototype semi-transparent photovoltaic modules for greenhouse roof applications. Biosystems Engineering, 122, pp.62–73.

[34] Cossu, M., Yano, A., Li, Z., Onoe, M., Nakamura, H., Matsumoto, T., Nakata, J., 2016, Advances on the semi-transparent modules based on micro solar cells: First integration in a greenhouse system. Applied Energy, 162, pp. 1042-1051.

[35] Cossu, M., Yano, A., Murgia, L., Ledda, L., Deligios, P.A., Sirigu, A., Chessa, F., Pazzona, A., 2017, Effects of the photovoltaic roofs on the greenhouse microclimate. Acta Horticulturae, 1170, pp. 461-468.

[36] Bot, G., Van De Braak, N., Challa, H., Hemming, S., Rieswijk, Th., Straten, G. V., Verlodt, I., 2005. The solar greenhouse: State of the art in energy saving and sustainable energy supply. Acta Horticulturae, 691, pp.501–508.

[37] Gelder, A., Dieleman, J.A., Bot, G.P.A., Marcelis, L.F.M., 2012, An overview of climate and crop yield in closed greenhouses. J. Hortic. Sci. Biotech., 87 (3) (2012), pp. 193-202

[38] Qian, T., Dieleman, J.A., Elings, A., Marcelis, L.F.M., 2012. Leaf photosynthetic and morphological responses to elevated CO 2 concentration and altered fruit number in the semi-closed greenhouse. Scientia Horticulturae, 145, pp.1–9.

[39] Opdam, J.J.G., Schoonderbeek, G.G., Heller, E.M.B., De Gelder, A., 2005. Closed greenhouse: A starting point for sustainable entrepreneurship in horticulture. Acta Horticulturae, 691, pp.517–524.

[40] Gelder, a., Heuvelink, E., Opdam, J.J.G., 2005. Tomato yield in a closed greenhouse and comparison with simulated yields in closed and conventional greenhouses. Acta Horticulturae, 691, pp.549–552.

[41] Qiana, T., Dieleman, J.A., Elings, A., De Gelder, A., Marcelis, L.F.M., Van Kooten, O., 2011. Comparison of climate and production in closed, semi-closed and open greenhouses. Acta Horticulturae, 893, pp.807–814.

[42] Bakker, J.C., De Zwart, H.F. & Campen, J.B., 2006. Greenhouse cooling and heat recovery using fine wire heat exchangers in a closed pot plant greenhouse: Design of an energy producing greenhouse. Acta Horticulturae, 719, pp.263–270

[43] Zwart, H.F., 2011. The sunergy greenhouse - One year of measurements in a next generation greenhouse. Acta Horticulturae, 893, pp.351–358.

[44] Sonneveld, P.J., Swinkels, G.L.A.M., Bot, G.P.A, Flamand, G., 2010. Feasibility study for combining cooling and high grade energy production in a solar greenhouse. Biosystems Engineering, 105(1), pp.51–58.

[45] Sonneveld, P.J., Swinkels, G.L.A.M., Campen, J., van Tuijl, B. A.J., Janssen, H.J.J., Bot, G.P.A., 2010. Performance results of a solar greenhouse combining electrical and thermal energy production. Biosystems Engineering, 106(1), pp.48–57.

[46] Loonen, R.C.G.M., Trčka, M., Cóstola, D., Hensen, J.L.M., 2013. Climate adaptive building shells: State-of-the-art and future challenges. Renewable and Sustainable Energy Reviews, 25, pp.483–493.

[47] Loonen R.C.G.M., Favoino, F., Hensen, J.L.M. & Overend, M. 2017. Review of current status, requirements and opportunities for building performance simulation of adaptive facades, Journal of Building Performance Simulation, Vol. 10, No. 2, pp. 205–22.

[48] Kimber, M., W. W. Clark, and L. Schaefer. 2014. "Conceptual Analysis and Design of a Partitioned Multifunctional Smart Insulation." Applied Energy 114 (February): 310–319

[49] Favoino, F. 2015. "Assessing the Performance of an Advanced Integrated Facade by Means of Simulation: The ACTRESS Facade Case Study." Journal of Facade Design and Engineering, vol. Preprint, no. Preprint: 1–23.

[50] Vanthoor, B.H.E., van Henten, E.J., Stanghellini, C.,de Visser, P.H.B., 2011. A methodology for model-based greenhouse design: Part 3, sensitivity analysis of a combined greenhouse climate-crop yield model. Biosystems Engineering, 110(4), pp.396–412.

[51] Vanthoor, B.H.E., 2011. A model based greenhouse design method — PhD thesis, Wageningen University, The Netherlands.

[52] Clarke, J.A., Energy Simulation in Building Design, edited by Clarke, J.A., Butterworth-Heinemann, Oxford, 2001, ISBN 9780750650823,

[53] Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002 "A fast and elitist multiobjective genetic algorithm: NSGA-II," in IEEE Transactions on Evolutionary Computation, vol. 6, no. 2, pp. 182-197

[54] Lee, C., 2017. Simulation-based performance assessment of climate adaptive greenhouse shells — PhD thesis. Eindhoven University of Technology, The Netherlands.

[55] Zwart, H.F., 1996. Analyzing energy-saving options in greenhouse cultivation using a simulation model— PhD thesis. Wageningen University, The Netherlands

[56] Fitz-Rodríguez, E., Kubota, C., Giacomelli, G., Tignor, M., Wilson, S., McMahon, M., 2010. Dynamic modeling and simulation of greenhouse environments under several scenarios: A web-based application. Computers and Electronics in Agriculture, 70(1), pp.105–116.

[57] Loonen R.C.G.M., Favoino, F., Hensen, J.L.M. & Overend, M. 2017. Review of current status, requirements and opportunities for building performance simulation of adaptive facades, Journal of Building Performance Simulation, Vol. 10, No. 2, pp. 205–22.

[58] ESP-rSource, Retrieved August 29, 2018, from https://github.com/ESP-rCommunity/ESP-rSource

[59] Strachan, P.A., Kokogiannakis, G., Macdonald, I.A., History and development of validation with the ESP-r simulation program, In Building and Environment, Volume 43, Issue 4, 2008, Pages 601-609, ISSN 0360-1323

[60] Beausoleil-Morrison, I., Macdonald, F., Kummert, M., Jost, R., McDowell, T., 2013. Co-simulation between ESP-r and TRNSYS: more highly resolved modelling of integrated building and energy systems. Proceedings of Building Simulation 2013, pp.3458–3465

[61] Lee, C., Costola, D., Swinkels, G. L. A. M. & Hensen, J.L.M. 2012. On the use of building energy simulation programs in the performance assessment of agricultural greenhouses, ASim, IBPSA-Asia, pp. 1-8.

[62] Machairas, V., Tsangrassoulis, A., Axarli, K., 2014. Algorithms for optimization of building design: A review, Renewable and Sustainable Energy Reviews, 31, Pages 101-112.

[63] Nguyen, A.-T., Reiter, S., Rigo, P., 2014. A review on simulation-based optimization methods applied to building performance analysis. Applied Energy, 113, pp.1043–1058.

[64] Trcka, M., 2008. Co-simulation for performance prediction of innovative integrated mechanical energy systems in buildings— PhD thesis. Eindhoven University of Technology, The Netherlands.

[65] Hoes, P., Hensen, J.L.M. 2016. The potential of lightweight low-energy houses with hybrid adaptable thermal storage: comparing the performance of promising concepts. Energy and Buildings, vol. 110, pp. 79-93.

[66] Wetter, Michael. (2011). Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed. Journal of Building Performance Simulation. 4. 185-203. 10.1080/19401493.2010.518631.

[67] Hoes, P. 2014 - Computational performance prediction of the potential of hybrid adaptable thermal storage concepts for lightweight low-energy houses – PhD thesis, Eindhoven University of Technology, The Netherlands

[68]Vanthoor, B.H.E., Gázquez, J.C., Magán, J.J., Ruijs, M.N.A., Baeza, E., Stanghellini, C., van Henten, E.J., de Visser, P.H.B., 2012. A methodology for model-based greenhouse design: Part 4, economic evaluation of different greenhouse designs: A Spanish case. Biosystems Engineering, 111(4), pp.336–349.

[69] Vermeulen, P.C.M., 2010, Kwantitatieve informatie voor de glastuinbouw, KWIN Glastuinbouw, Retrieved August 29, 2018, from http://edepot.wur.nl/326466

[70] Hensen, J.L.M., 1999. A comparison of coupled and de-coupled solutions for temperature and air flow in a building, ASHRAE Transactions, vol. 105:2, pp. 962-969, American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

[71] The Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut, KNMI), Retrieved August 29, 2018, https://climexp.knmi.nl/start.cgi

[72] Loonen, R.C.G.M. & Hensen, J.L.M. 2013. Dynamic sensitivity analysis for performance-based building design and operation. Proceedings of Building Simulation 2013: 13th Conference of the International Building Performance Simulation Association IBPSA, 26-28 August, Chambery, pp. 299 – 305.